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The Use of Recycled Polyethylene Terephthalate as a Partial Replacement for Sand on the Mechanical Properties of Structural Concrete

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Abstract

Negative environmental impacts caused by the over-extraction of sand have arisen due to the high demand of global concrete production. Subsequently, the need to find an adequate replacement for sand in concrete production is paramount. Additionally, the mismanagement of plastic waste in Southeast Asia has resulted in large quantities being sent to landfill. This could otherwise be used as a viable alternative. Several studies have investigated the effect of Polyethylene Terephthalate (PET) aggregate as a partial replacement for sand on the mechanical, durability and physical properties of concrete. Nevertheless, due to the broad number of variables affecting the properties of concrete, gaps remain in the literature suggesting the necessity for a more comprehensive approach. The aim of this research was therefore to investigate the impact on strength when using Polyethylene Terephthalate (PET) flakes in concrete. The effects of substituting 10 % and 20 % of sand by volume with recycled PET flakes were investigated, with the results compared to reference mix samples. 20 cube samples, of sizes 100 mm^3 and 150 mm^3, were cast for compressive strength tests; 20 cylinder samples, of sizes 100 ømm x 150 mm and 150 ømm x 300 mm, were manufactured for splitting tensile strength tests; and 9 prism samples, of size 100 mm x 100 mm x 500 mm were cured for flexural strength and modulus of elasticity tests. All 49 samples were tested for dry density. A constant curing age of 28 days and a water-to-cement ratio of 0.5 were applied to this experiment. The size of the PET flakes used in the concrete mixes were between 0 and 10 mm. The results indicated that an initial decrease in the compressive strength and modulus of elasticity for 10% replacement level was seen before an increase in strength for 20% replacement. Contrastingly, an initial increase in flexural strength for 10% replacement was exhibited, before a decrease in strength for 20% replacement. The splitting tensile strength and hardened density showed a growing decrease in values for increasing replacement percentage. The conventional reference concrete mixes underwent brittle failure; whereas ductile behaviour was shown by the mixes containing PET flakes. Accordingly, it was concluded that there is significant potential for the use of up to 20 % replacement of PET in a suitable mix design for structural and non-structural applications.

Introduction

Both humans and animals now live in a world where plastic is ubiquitous. The slow rates of degradation mean that the dumping of such material is a long-term environmental concern. The high costs associated with plastic recycling have limited its capacity for effective waste management. In some Southeast Asian countries, it has been reported that over 75 % of the accumulated plastic waste is mismanaged, with 6 Asian countries responsible for 60 % of the plastic that ends up in the ocean (UNEP, 2018). Recently governments have started to acknowledge the issue of plastic waste, with China announcing a ban on all imports of plastic waste in December 2017 (Brooks et al., 2018) and the UK investing £61.4 million in the Commonwealth Clean Oceans Alliance in April 2018 (HM Treasury, 2018). Despite this, finding a use for the ever-growing volume of plastic waste is now more important than ever.

A different problem arises from the uses of sand. For example, most notably in India, where restrictions on the extraction of sand have risen as a result of over-extraction. Despite a ruling by the high court in 2010 banning sand mining across the state of Mumbai (Zeenews, 2010), the documentary 'Sand Wars, an investigation documentary' revealed that 110,000 to 120,000 tons of sand were still being removed from beaches and the river basin in Tamil Nadu, India every day (2013). This need for sand has been fuelled by the rising demand from the construction industry.

With both the sand and plastic problems stemming from similar geographical areas, the proposed partial replacement of sand with waste plastic in concrete mixes would provide a viable solution. Further encouraging the collection of plastic waste whilst simultaneously allowing the regrowth of natural habitats by reducing the need for fine construction sand.

The aim of this study is to investigate the impact on strength when using Polyethylene Terephthalate (PET) flakes in concrete.
Objectives:

1. To carry out an extensive literature review in the area of concrete with PET flakes.
2. To conduct tests to determine the tensile, compressive and flexural strength of concrete with PET flakes.
3. To analyse the test results and provide guidance on the use of PET in concrete.

Literature Review

Plastic uses in concrete

Since the invention of the first synthetic plastic, Bakelite, in 1907 there has been an estimated 8.3 Bt of plastic produced worldwide (Geyer et. al, 2017). PET plastic, now the most frequently used plastic, was first synthesised in 1941 and the technology for producing mass consumer plastic goods was unlocked; shortly after leading to an increase from 2 Mt (1950) to 380 Mt (2015) in annual global production of plastic fibres and resins (Geyer et. al, 2017). The type of plastic chosen to be used in a concrete mix can have a significant effect on its overall performance (Thorneycroft et al., 2018). Their properties dictate the use in practical applications.

Effects of PET for use in concrete construction

Since the invention of the first synthetic plastic, Bakelite, in 1907 there has been an estimated 8.3 Bt of plastic produced worldwide (Geyer et. al, 2017). PET plastic, now the most frequently used plastic, was first synthesised in 1941 and the technology for producing mass consumer plastic goods was unlocked; shortly after leading to an increase from 2 Mt (1950) to 380 Mt (2015) in annual global production of plastic fibres and resins (Geyer et. al, 2017). The type of plastic chosen to be used in a concrete mix can have a significant effect on its overall performance (Thorneycroft et al., 2018). Their properties dictate the use in practical applications.

Testing undertaken by researchers in Portugal looked at the partial substitution of natural aggregate with three different forms of plastic waste aggregate. These varied in shape, size and texture: i) 2-5 mm flaky shredded fine plastic aggregate (PF) ii) 10-20 mm shredded coarse plastic aggregate (PC) iii) 3 mm spherical heat-treated pellet-shaped plastic aggregate (PPe) (Saikia and Brito, 2013). An increase in corporation for both the fine and coarse plastic aggregates, resulted in a greater w/c ratio. On the other hand, the smooth spherical nature of the plastic pellet aggregates was rationale for the lower w/c values. As the content of PET-aggregates increased, the compressive strength was seen to decrease regardless of type. However, the higher compressive strength of the PPe aggregates was attributed to the lower w/c ratio. Despite this, for 5 % substitution, the PF and PPe aggregates had roughly the same strength. This is a result of the rough shape and texture of the PF aggregates as well as the similar size distribution with respect to the natural aggregate (Saikia and Brito, 2013).

Albano et al. (2009) conducted tests on concrete mixes containing ‘small’ (0.26 cm) and ‘big’ (1.14 cm) PET particles. Resultantly, the mixes with 10 % replacement of sand with small and 50/50 PET particle sizes exhibited the highest compressive strength values in comparison to mixes with bigger particle size and greater content. Consequently, the increased cavities and pores introduced by the larger particles was reason for the significantly low compressive strength seen in the mixes containing 20 % replacement of big PET particles. It must also be noted that the lower w/c ratio of 0.50 further enhanced the compressive strength of all the concrete mixes.

Rahmani et al. (2013) undertook tests on concrete containing fine PET particles, as described above, for replacement levels of 5 %, 10 % and 15 % of sand, by volume. Tests were undertaken using w/c ratios of 0.42 and 0.54 for replacement levels of 5 %, 10 % and 15 % by volume. The greater specific surface area of the PET particles compared to that of the sand replacement was noted to reduce the workability due to the increased friction between the particles (Rahmani et al., 2013). It was also seen that, as the volume of PET particles increased, the compressive strength decreased.

It was concluded by Suganthy and Chandrasekar (2013) that a rapid decrease in compressive strength occurred after 25 % replacement of sand with plastic waste. For use in sustainable lightweight structural applications, both density and compressive strength requirements of a concrete mix must be met. Over 25 % replacement will provide adequate density however will greatly hinder the compressive strength (Alqahtani et al., 2017).

Thorneycroft et al. (2017) followed the BS EN 12390-2:2009 code for preparing and casting of 10 mixes with different types and grading of plastic. The plastic was initially sieved to obtain a grading curve which was subsequently compared to the fine sand. In order to account for the hydrophobic nature of plastic the dry ingredients, including the plastic, were first mixed for one minute before the addition of cement and water in several increments. The mix design of Rahmani et al. (2013) was undertaken similarly to that of Thorneycroft et al. (2017). Half of the sand (fine aggregate), all of the gravel (coarse aggregate) and the PET particles were initially mixed before being saturated by 20 % of the water. The remaining sand and cement were then added, preceding the addition of the remaining water in increments. The initial incorporation of plastic and natural aggregates before the addition of the binding elements promotes an even spread of plastic throughout the mix. This also reduces the potential for segregation between the plastic and cement matrix, following the addition of the water.

Thorneycroft et al. (2017) studied the effect that different types of plastic additive had on the behaviour of concrete cubes subjected to compressive load. Eleven novel concrete mixes were cast to determine a suitable material to be used as partial replacement for fine sand in a structural concrete mix. The effect of particle size supports the work by Saikia and Brito (2013) showing that as the size of the particles increases, the compressive strength decreases.

The experiments undertaken by Juki et al. (2013) and Choi et al. (2005) showed the most comparable results, with splitting tensile strength decreases of 15 %, 32 % and 43 % and 19 %, 31 % and 38 %, respectively, shown for plastic replacement levels of 25 %, 50 % and 75 %. The reason for this being the materials used in each study. Both used coarse aggregate with a maximum size of 20 mm and sand as fine aggregate. A definitive trend emerges when reviewing splitting tensile strength in previous papers, that a decrease in strength is seen with the inclusion, and increasing content, of plastic waste in concrete. The reduced bond strength between the PET and cement paste, as a result of the smooth surface texture of the particles was reason for this (Frigione, 2010; Rahmani et al., 2013; Alqahtani et al., 2017). As stated earlier, the porosity of a concrete mix is increased with the inclusion of plastic particles. Thus, the resultant increase in w/c ratio was also held accountable for the decrease in splitting tensile strength by Albano et al. (2009) and Frigione (2010).

Yang et al. (2015) undertook flexural tests on concrete beams with dimensions 150 mm x 150 mm x 550 mm. Recycled polypropylene (PP) particles were ground to between 1-5 mm and were subsequently used to replace 10 %, 15 %,20 % and 30 % of fine aggregate by volume. The resulting values were seen to give an increase in flexural tensile strength up to a replacement level of 15 %, before gradually reducing as the plastic replacement percentage increased. This behaviour was said to correlate to the compressive strength and splitting tensile strength results obtained in the study. This relates directly to the compressive strength trend described above, with the reduction in strength attributed to the weak ITZ between the cement paste and the face of the plastic aggregate (Yang et al., 2015). It must be noted that the low water-to-binder ratio of 0.25 had a significant effect on increasing the overall strength of the concrete. This was evident by the increased compressive strength and splitting tensile strength value of the mixes up to 20 % replacement in comparison to the reference mix.

Despite using a three-point loading setup, Hannawi et al. (2010) also undertook flexural tests on concrete containing partial volumetric replacement of fine aggregates. Replacement proportions of 3 %, 10 %, 20% and 50% of PET plastic were used in prismatic beams of size 40 mm x 40 mm x 160 mm with a w/c ratio of 0.5. Corresponding to the reasoning above, the overall flexural strength results were greater than those experienced by Yang et al. (2015). Nevertheless, a similar trend as acquired for the mixtures containing up to 10% replacement. When compared to the reference mix, an initial increase in flexural strength, before a gradual decrease, was shown as the replacement level increased.

The properties of the mixes produced by Marzouk et al. (2007) align to those shown in the study by Hannawi et al. (2010). Both use beam sizes of 40 mm x 40 mm x 160 mm, w/c ratios of 0.5 and plastic replacement percentages of 10 %, 20 % and 50 %. Along with the results obtained by Rahmani et al. (2013), both studies fundamentally reinforce the trend experienced by Hannawi et al. (2010). When compared to the reference mix, no outstanding changes are seen by the mixes containing up to 10% replacement level of PET. Following this, a gradual decrease in strength is experienced for increasing plastic percentage.

For isotropic and homogenous materials, the flexural modulus of elasticity of a material is interchangeable with that of the tensile Young's modulus (Otani et al., 2014). With the inclusion of micro-cracks and pores however, this is not the case. A number of studies evidence this, showing greater flexural strength values when compared to tensile strength (Alqahtani et al., 2017; Rahmani et al., 2013; Saikia and Brito, 2014; Yang et al., 2015; Batayneh et al., 2007). Despite this, a common trend is experienced for studies that investigated both flexural and tensile modulus of elasticity. Both papers by Hannawi et al. (2010) and Jacob-Vaillancourt and Sorelli (2018) measured modulus of elasticity values from cylindrical samples corresponding to up to 30% of the residual compressive strength. The trends subsequently follow those of the compressive strength values obtained by both authors. The elastic modulus was seen to decline with increasing replacement level of plastic aggregate. Four factors were attributed to the lowering modulus values (Hannawi et al., 2010; Jacob-Vaillancourt and Sorelli, 2018):

a) Weakened interface between the plastic aggregate and the cement paste
b) Increased crack propagation as a result of increased stress concentration zones
c) Increased air content
d) Lower elastic modulus values of the plastic aggregate compared to the natural aggregate

Desirable properties of the use of PET in concrete include enhanced impact resistance/energy absorption capacity (Bhogayata and Arora, 2018; Ismail and Al-Hashmi, 2008; Saxena et al., 2018), lower density (Choi et al., 2009; Ferreira et al., 2012; Silva et al., 2013) and increased ductile behaviour (Babu et al., 2005; Frigione, 2010; Tandon and Faber, 1993). All of which are the result of the semi-crystalline microstructure and morphology of PET. The pores seen in concrete contribute to its low tensile capacity. However, it still exhibits a quasi-brittle nature, providing a measure of deformation prior to failure (Tandon and Faber, 1993). The ability to deform plastically and compress under stress means that the plastic lowers the stiffness of concrete by preventing the interaction between stiff aggregates and cement paste (Frigione, 2010). Research undertaken by Frigione (2010) and Babu et al. (2005), found that the ultimate strain of the respective concrete mixes increased as the volume of PET particles increased.

Nevertheless, a key weakness associated with PET, and plastic in general, including is its hydrophobic nature. This prevents strong bonding and adherence with concrete elements. Ferreira et al. (2012) attributed the decrease in compressive strength of concrete samples, containing 7.5 % and 15 % replacement of natural aggregate with fine, coarse and pellet-shaped PET aggregate, to the low affinity of the plastic aggregate; with water limiting the hydration process and subsequently causing a decline in the bond strength. Furthermore, Islam et al. (2016) concurred that, when undertaking tests on concrete using 0 %, 20 %, 30 %, 40 % and 50 % replacement of brick chips with PET coarse aggregate, bleeding caused by an increased w/c ratio resulted in the accumulation of water in the Interfacial transition zone (ITZ). This prevented adequate bonding between the cement paste and plastic aggregate. Additionally, the smooth surface of plastic aggregate reduces the effect of aggregate interlock, leading to poor anchorage between plastic aggregate and the cement matrix (Islam et al., 2016; Gu and Ozbakkaloglu, 2016).

Justification and conclusion

From the analysed studies above, it is evident that there is a significant potential for the use of PET as a partial replacement of sand. By carefully assessing the various properties of concrete (w/c ratio, plastic percentage, etc.), the following mix design and experiment used in this study was carried out to achieve the overarching aim: to investigate the impact on strength when using Polyethylene Terephthalate (PET) flakes in concrete

Past 10 % volumetric replacement of sand with PET aggregate, an increasing reduction in the mechanical properties of concrete was experienced for increasing replacement ratios. This was attributed to the weak ITZ and bonding between the PET aggregate and the cement paste, as well as an increase in voids due to the hydrophobic behaviour of the PET. However, no two papers' results are the same due to the large variability in the properties of PET and the various mix designs used. For this reason, there is a need for a reproducible mix design which can be implemented on site which produces consistent results. It appears that the use of flaked angular plastic particles of small, but varying, grade provided the most effective way of minimising strength loses. The papers by Marzouk et al. (2006), Albano et al. (2009), Rahmani et al. (2013), Saikia and Brito (2013) and Thorneycroft et al. (2018) were of particular pertinence to this study. The changed and tests properties of the mix designs created in each study were used to give particular guidance for this experiment. The conclusions of which led to the prediction that the density and mechanical strength of the concrete would decrease for increased PET content.

Experimental work

A set of concrete samples were prepared and cast in accordance with BS EN 12390-2:2009 (BSI, 2009a), with guidance taken from Teychenné et al. (1988). A constant water-to-cement ratio (w/c) of 0.5 allowed the materials to be easily combined whilst ensuring a workable mix without the need for a superplasticiser, as seen in other studies (Saikia and Brito, 2013; Yang et al., 2015).

Materials

Cement

Rugby® High Strength CEM I 52,5N Portland cement was used conforming to BS EN 197-1, with a density of 2800-3200 kg/m^3 and a mean particle size of 5-30 μm.

Aggregates

Locally-sourced crushed granite from Hingston Down Quarry was used as coarse aggregate. This was available in two gradings: G_c85/20 10/20 (maximum 20mm) and G_c85/20 4/10 (maximum 10mm) “single sized”. A mixture of the two grades was used in the ratio of 2:1 to minimise air voids. A typical relative density of 2.7g/cm^3 was measured SSD. The fine aggregate made use of local ‘secondary’ waste sand from China clay extraction, 60 % of which passed through a 0.6 mm sieve.

PET flakes

The flaked PET plastic waste used as aggregate, as seen in Figure 1, was supplied by the commercial plastic recycling company Clean-Tech, from a plant in Hemswell, Lincolnshire, UK. The PET particles went through a vigorous process where recycled plastic bottles were initially removed of small particles and metals before being sort by polymer and colour. The clear PET used in this study (80 % clear and 20 % blue) was then passed through a granulator and the remainder of contaminants were finally removed by washing and air dryers (Clean Tech Ltd., 2018).

Figure 1: PET Plastic Aggregate

Preparation of concrete samples

The concrete was made in a standard 50L concrete mixer. All ingredients were measured out separately prior to the batching process for efficiency, in the total quantities shown in Table 1. Cube specimens with 100 mm^3 and 150 mm^3 dimensions, cylindrical specimens with 100 ømm x 200 mm and 150 ømm x 300 mm dimensions and beam specimens with 100 x 100 x 500 mm dimensions were prepared from the fresh concrete mixtures.

Table 1*:* Concrete mix Design

Batch quantities for reference concrete samples (R1)

Mix reference	Cement CEM I 52.5N (kg)	Water (kg)	Fine aggregate*1 (kg)	Coarse aggregate *2 (kg)		Plastic (kg)	Plastic (%)
				10mm	20mm		
100 mm^3	0.45	0.23	0.63	0.36	0.72	0.00	0.00
150 mm^3	1.52	0.76	2.13	1.20	2.41	0.00	
100 øx200 mm^3	0.71	0.35	0.99	0.56	1.12	0.00	
150 øx300 mm^3	2.39	1.19	3.34	1.88	3.79	0.00	
100 x100 x500 mm^3	2.25	1.13	3.15	1.78	3.58	0.00	
Total (4 samples +10%)	23.91	11.95	33.47	18.86	37.99	0.00	

Batch quantities for concrete samples with 10% plastic replacement (P10)

Mix reference	Cement CEM I 52.5N (kg)	Water (kg)	Fine aggregate*1 (kg)	Coarse aggregate *2 (kg)		Plastic (kg)	Plastic (%)
				10mm	20mm		
100 mm^3	0.45	0.23	0.57	0.36	0.72	0.0141	10.00
150 mm^3	1.52	0.76	1.91	1.20	2.41	0.0497	
100 øx200 mm^3	0.71	0.35	0.89	0.56	1.12	0.0221	
150 øx300 mm^3	2.39	1.19	3.01	1.88	3.79	0.0745	
100 x100 x500 mm^3	2.25	1.13	2.84	1.78	3.58	0.0702	
Total (3 samples +10%)	23.91	11.95	30.12	18.86	37.99	0.7536	

Batch quantities for concrete samples with 20% plastic replacement (P20)

Mix reference	Cement CEM I 52.5N (kg)	Water (kg)	Fine aggregate*1 (kg)	Coarse aggregate *2 (kg)		Plastic (kg)	Plastic (%)
				10mm	20mm		
100 mm^3	0.45	0.23	0.50	0.36	0.72	0.03000	20.00
150 mm^3	1.52	0.76	1.70	1.20	2.41	0.10603	
100 øx200 mm^3	0.71	0.35	0.79	0.56	1.12	0.04712	
150 øx300 mm^3	2.39	1.19	2.67	1.88	3.79	0.15904	
100 x100 x500 mm^3	2.25	1.13	2.52	1.78	3.58	0.15000	
Total (3 samples +10%)	23.91	11.95	26.78	18.86	37.99	1.6095	

*1 crushed sand graded with percentage finer than 0.6mm 60% and density 1.66g/cm3

*2 angular, maximum 20mm diameter crushed granite density 2.6 g/cm3

Method

The dry ingredients, including the plastic aggregate, were first mixed for one minute to increase the potential roughness of the plastic. Following this, the water was added in 2L increments over a 1-minute time-period to reduce the potential for separation of the plastic from the concrete matrix. The concrete was mixed for a further two minutes, for the R1 and P10 batches, and three minutes for the P20 batch, before being transferred to moulds. The notable increase in mix duration correlates to that of previous studies (Rahmani et al., 2013). The wet concrete was placed into the moulds in three stages. Each time being compacted by hand, using a tamping rod, and vibration, using a vibrating poker. Once full, any excess concrete was struck flush using a trowel and the samples were stored at room temperature. All samples were demoulded after one day. After being cured in water with a constant temperature of 20°c for a total of 28 days, the concrete samples were initially weighed, both submerged in water and following surface drying; before being subject to mechanical testing.

Strength testing

Compression tests

Compression testing of the concrete cubes was undertaken in accordance with BS EN 12390-3:2009 (BSI, 2009b) using the apparatus shown in Figure 2,a. The lower rate of the applied axial compressive load for the 100 mm^3 and 150 mm^3 cubes were 3 kN/s and 9 kN/s, respectively, using an automated hydraulic jack.

Splitting tensile strength

In accordance with BS EN 12390-6:2009 (BSI, 2009d), splitting tensile strength testing was undertaken on the cylinders by applying a force equally along the vertical axis of the samples, shown in Figure 2,b. The lower rates of the applied load for the 100 mm diameter and 150 mm diameter cylinders were 1.5 kN/s and 3.5 kN/s, respectively.

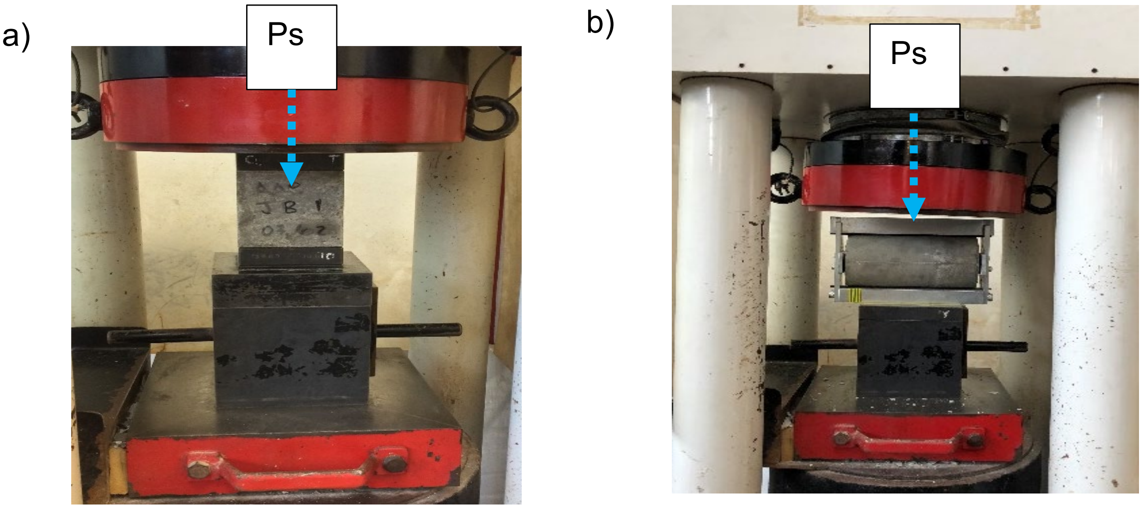

Figure 2: a) compressive and b) split tensile strength tests

Flexural strength

Flexural strength of the concrete beams was tested in accordance with BS EN 12390-5:2009 (BSI, 2009c), with a support span of 300 mm and a loading rate of 0.167 kN/s, as shown in Figure 3.

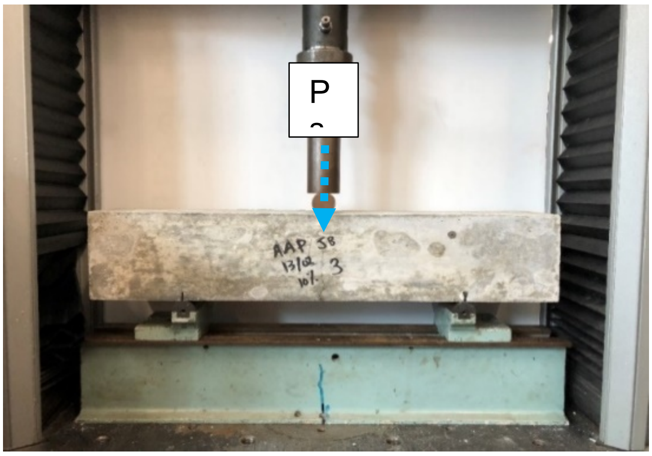

Figure 3*:* Flexural test

Scanning Electron Microscopy (SEM)

A JEOL 6610 LV SEM machine was used to take pictures of the interfacial zone between the cement/concrete matrix and the plastic aggregate. The samples were taken by further crushing the tested cubes and cylinders, before being placed in the machine. Low vacuum mode was chosen to allow gas into the chamber to prevent the need for the samples to be coated in gold, or similar, due to the low conductivity of both concrete and plastic. The low vacuum mode was combined with a backscattered electron detector to configure images up to a magnification of x2,000.

Results

Analysis of the PET particle concentration on the mechanical strength of concrete can be drawn from Table 2 a-e.

Table 2: Test results

a)

Mix design:	Density (kg/m^3)												
	Reference					10 % replacement level				20 % replacement level			
	Sample 1	Sample 2	Sample 3	Sample 4	Average	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
100 mm^3	2358.6	2359.3	2348.9	2354.5	**2355.3**	2324.6	2342.3	2331.7	**2332.9**	2308.6	2288.5	2318.9	**2305.3**
150 mm^3	2345.5	2349.2	2343.7	2347.3	**2346.4**	2323.7	2322.8	2324.3	**2323.9**	2311.3	2327.6	2319.6	**2318.6**
100 ømm x 200 mm	2344.8	2347.4	2350.1	2337.9	**2345**	2343.2	2358.6	2338.2	**2340.2**	2342.9	2312.7	2323.4	**2315.8**
150 ømm x 300 mm	2350.8	2354.8	2341.3	2353.9	**2350.2**	2323.6	2338.4	2332.1	**2337.9**	2317.8	2309.8	2311.4	**2321.4**
100 mm x 100mm x 500 mm	2356.8	2361.9	2388.6	-	**2369.1**	2374.2	2360.5	2372.2	**2352.1**	2322.9	2318.2	2305.7	**2315.6**

b)

Mix design:	Compressive strength (kN/m^2)												
	Reference					10 % replacement level				20 % replacement level			
	Sample 1	Sample 2	Sample 3	Sample 4	Average	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
100 mm^3	46.4	47.1	47.6	47.7	**47.2**	43.1	45.4	47.7	**45.4**	48	47.2	46.9	**47.4**
150 mm^3	48.2	47.9	46.9	48	**47.8**	46.5	46.5	47.4	**46.8**	50.2	47.9	49.2	**49.1**

c)

Mix design:	Tensile strength (kN/m^2)												
	Reference					10 % replacement level				20 % replacement level			
	Sample 1	Sample 2	Sample 3	Sample 4	Average	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
100 ømm x 200 mm	3.9	4.2	3.9	-	**4**	3.8	3.6	4.2	**3.9**	3.7	3.6	3.8	**3.7**
150 ømm x 300 mm	3.3	3.5	3.2	3.1	**3.2**	3.1	3.4	3.1	**3.2**	3.1	3.1	3.3	**3.2**

d)

Mix design:	Flexural strength (kN/m^2)												
	Reference					10 % replacement level				20 % replacement level			
	Sample 1	Sample 2	Sample 3	Sample 4	Average	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
100 mm x 100mm x 500 mm	6.9	6.3	6.6	-	**6.6**	6.6	6.6	7.1	**6.8**	6.3	6.6	5.6	**6.5**

e)

Mix design:	Bending modulus												
	Reference					10 % replacement level				20 % replacement level			
	Sample 1	Sample 2	Sample 3	Sample 4	Average	Sample 1	Sample 2	Sample 3	Average	Sample 1	Sample 2	Sample 3	Average
100 mm x 100mm x 500 mm	2894.9	2779.8	2926.8	-	**2867.2**	2333.2	2678.2	2704.4	**2571.9**	2954	3095	2850.1	**2966.3**

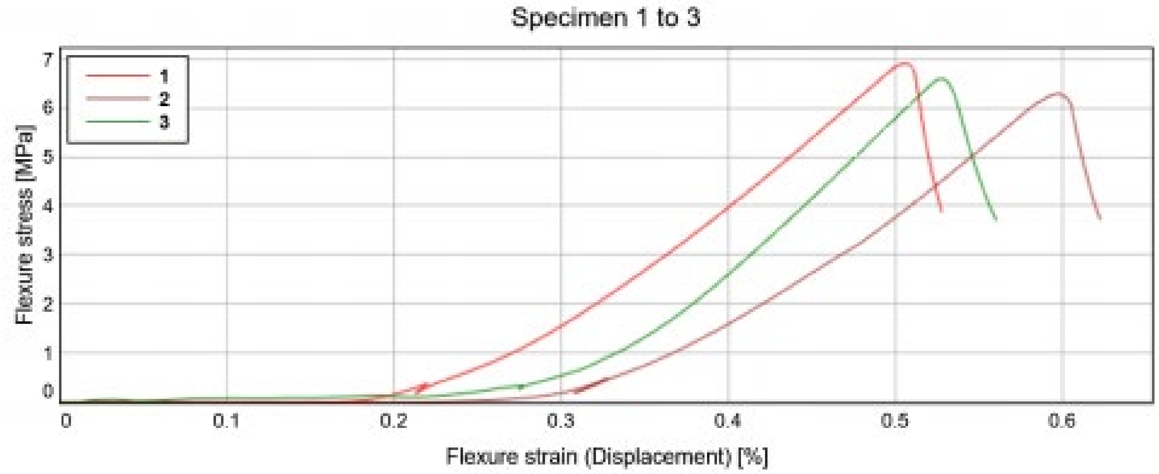

Figure 4: Flexural stress-strain graph for reference mix samples

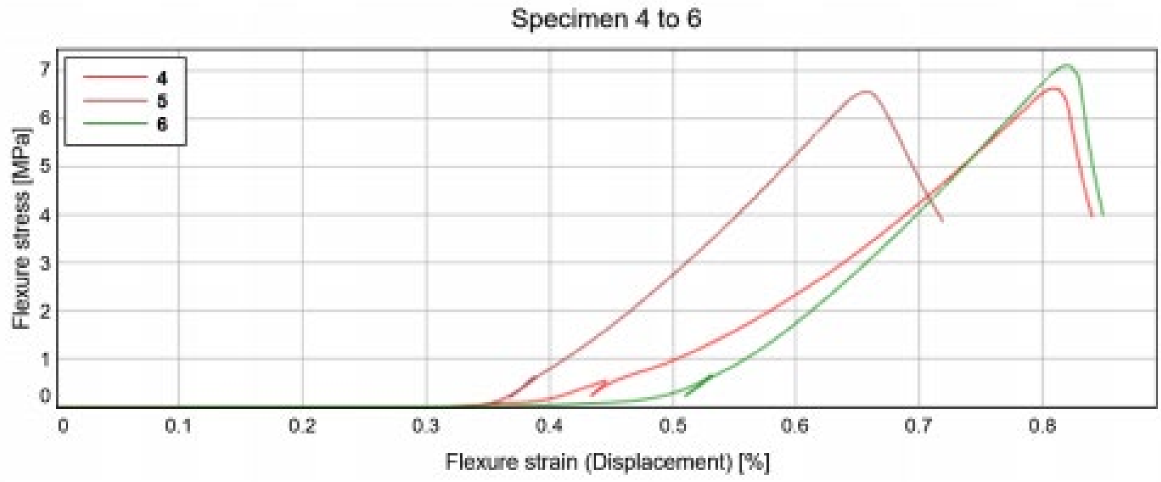

Figure 5: Flexural stress-strain graph for mix containing 10 % PET replacement

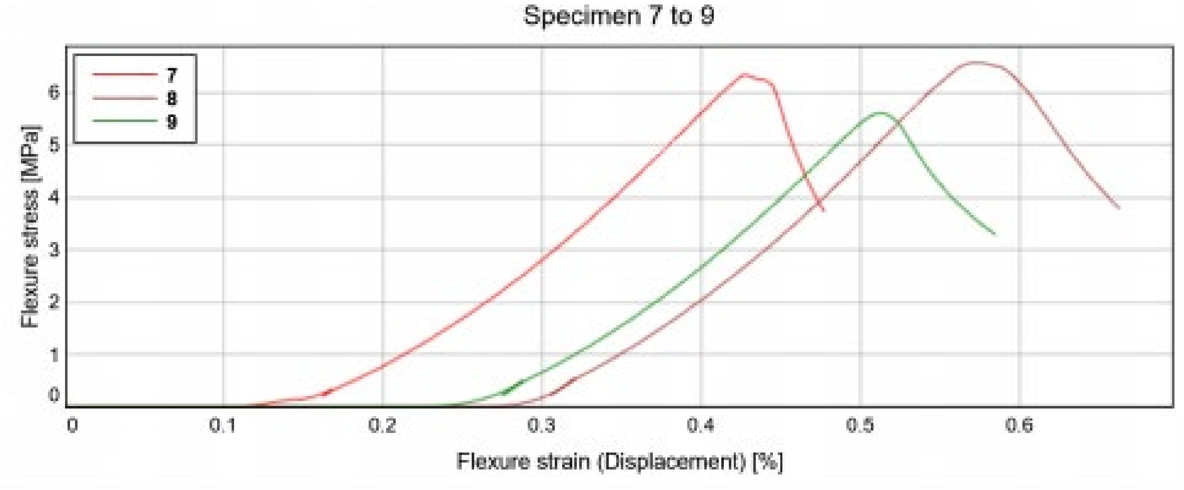

Figure 6: Flexural stress-strain graph for mix containing 20 % PET replacement

The flexural stress-strain graphs are shown in Figures 5, 6 and 7. Specimens 1-3 (Figure 5) relate to samples 1-3 of the reference mix, specimens 4-6 (Figure 6) relate to samples 1-3 for the mix containing 10% PET replacement, and specimens 7-9 (Figure 7) relate to samples 1-3 for the mix with 20% replacement of sand with PET.

Analysis

No issues were experienced during the experimental testing of the samples. For the strength tests, visual inspection following failure of the samples indicated that the maximum load had been reached. All surfaces were cleaned prior to testing to remove any debris and reduce the effect this might have had on the test results. However, for the compressive strength tests, due to the slight variability in size of the samples, the guide slabs were not able to transfer load across the full face of the cubed samples, the edges of which are shown in red in Figure 8. In any case, this would have had a minimal effect on the final strength values.

Figure 8: Concrete cube sample

Density

The resultant density of the concrete mixes with the addition of plastic aggregate agrees with the results described above (Ismail and Al-Hashmi, 2008; Ferreira et al., 2012), as well as the studies critiqued by Gu and Ozbakkaloglu (2016). A reduction in density of 0.67 % and 1.61 % for the mixes containing 10 % and 20 % plastic aggregate replacement (PA), respectively, was observed in comparison to the reference mix. The reduction in density can be attributed to the 80 % decrease in bulk density between the PET flakes and the crushed granite, as well as the increase in pores formed with the inclusion of plastic aggregate.

Surprisingly, the average decrease in density obtained from Table 2, between the concrete mixes containing 10 % and 20 % plastic replacement and the reference mix, are 2.0 % and 4.0 %, respectively. This discrepancy is due to round-off measurement errors of the materials as well as a loss of water experienced over the curing time.

The low variability in densities between the five test sample sizes implies an adequate mix of materials was achieved (Figure 9), thus confirming the experimental method used in this study. A subsequent reduction in the overall cost of a project can be obtained as a result of the reduced dead load on a structure. This therefore helps reduce the size of supporting elements making them easier to transport and handle.

Figure 9: Concrete beam with 20 % plastic

Compressive strength

Whilst the trends described in the literature show either:
a) a decrease in strength with the addition of plastic aggregate, regardless of plastic percentage (Jibrael and Peter, 2016; Saikia and Brito, 2013) or;
b) an initial increase in strength for concrete mixes up to a replacement ratio of 10 % (Rahmani et al., 2013; Thorneycroft et al., 2018), before a general decrease in strength as the replacement of plastic particles increased.
The results of the present experiment are in contrast; a decrease in strength shown by the lowest volumetric percentage of plastic (P10) was exhibited, before a higher strength gain was shown by the concrete with 20 % plastic aggregate replacement of sand (P20). The small changes in strength correlate well with the results of Thorneycroft et al. (2018), Rahmani et al. (2013) and Choi et al. (2005). However, they are less than the majority of similar mixes reported in the literature.

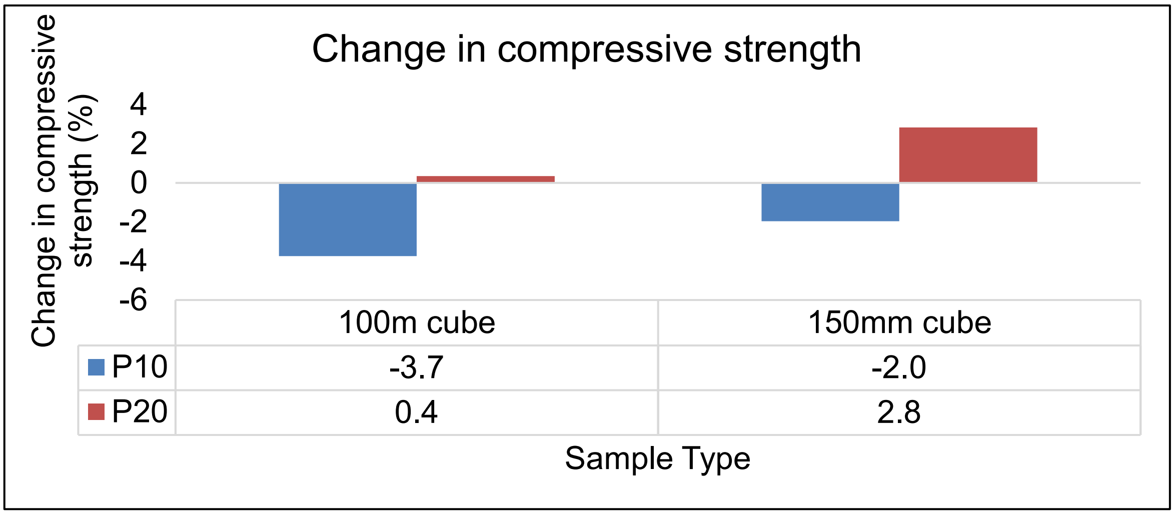

Figure 10: Percentage change in compressive strength of the mixes containing PET compared to reference mix

The greatest change in compressive strength can be seen by a decrease of 3.7 % for the 100 mm^3 cube samples with 10 % replacement of plastic aggregate, shown in Figure 10. This is due to the poor bonding between the plastic and the cement paste of sample one (Figure 11). Segregation of the concrete matrix resulted in large

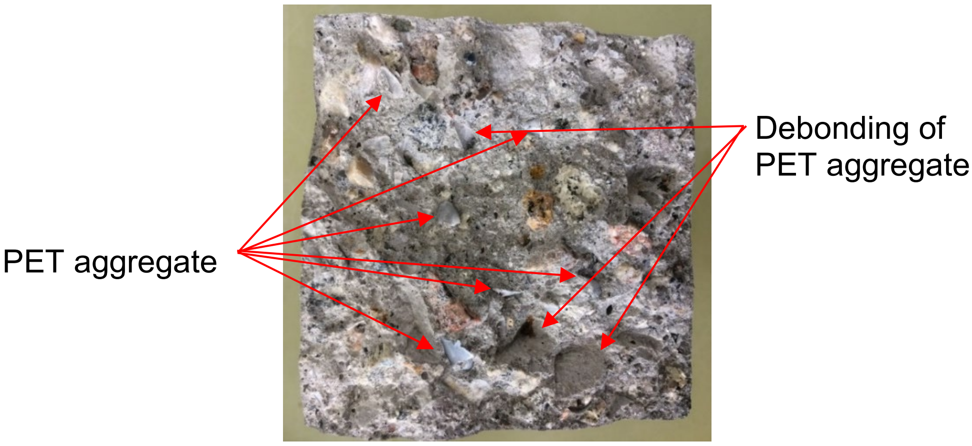

Figure 11: Debonding of PET flakes in 100 mm^3 P10 mix sample

honeycomb shaped pores and cavities on the surface has affected the compaction. The transverse stress cracks from the compression test are clearly focused around the pores on the edges of the sample, which act as defects producing areas of weakness. As a consequence of the Poisson effect, the sample undergoes lateral expansion which results in the addition of lateral shearing stresses (BREINS, 2019). Comparing the samples in Figure 12, it is evident that the level of segregation is not the same; this can be attributed to the varying properties associated with the concrete mix. By regarding sample one as an anomaly, the average decrease in compressive strength drops to 1.3 % when compared to the reference mix. Despite this, the three mixes gave compressive strengths that were similar in value and support the work done by Rahmani et al. (2013) and Thorneycroft et al. (2018), showing that a negligible effect on concrete compressive strength is seen for a 10 % replacement level.

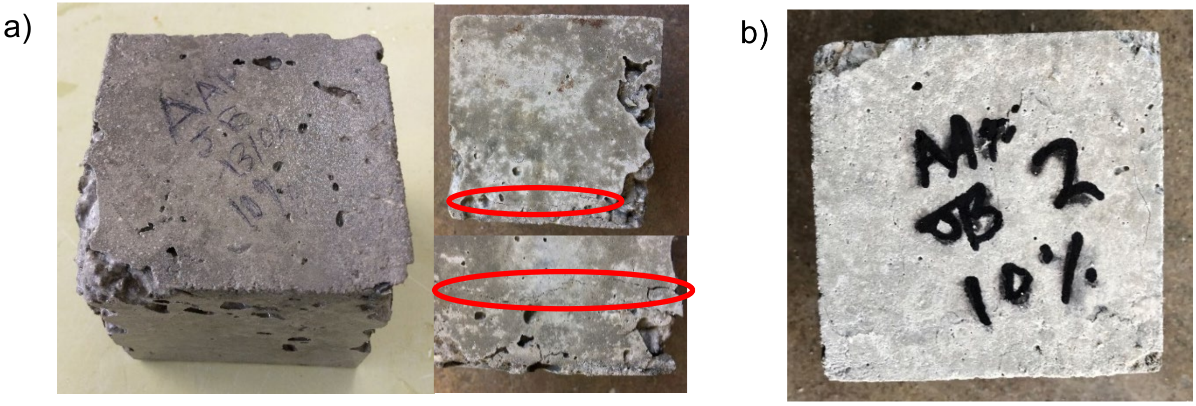

Figure 12: 100 mm^3 sample for 10 % replacement level a) sample 1 - compressive test failure shown in red b) sample 2

The unusual increase in strength shown by the cube samples with 20 % replacement of plastic aggregate can be understood by analysing the properties of the PET plastic and how they affect the hardened concrete mix. The greatest compressive strength shown by any 100 mm^3 specimen was sample 1, for 20 % replacement of plastic, shown in Figure 13. It is evident from the right hand photo, that whilst cracking occurred along the side faces of the cube, no significant interface failure has occurred. Interestingly, the cracks can also be seen to propagate at perpendicular angles implying that at maximum load the sample was in both compression and tension - a possible reason for this increase in compressive strength.

The angular and irregular shape of the plastic could have led to enhanced interlock between the plastic and the cement paste. After splitting open the sample in Figure 1X it can be seen that large cavities are present where weak bonding between the smooth face of the flakes and the cement paste has developed. However, it is also evident that the remaining flakes left in the concrete stick out from the shear plane. Due to the way in which the concrete cubes are tested, allowing lateral expansion, as shown in Figure X, the elastic properties of PET allow it to deform and increase toughness by crack arrest when subject to a maximum compressive force. This subsequently enhanced the strength of the concrete. This would imply that the PET flakes acted like fibres in the concrete, which has been seen to enhance the compressive strength of concrete mixes (Han et al., 2005; Ochi et al., 2007; Song et al., 2005).

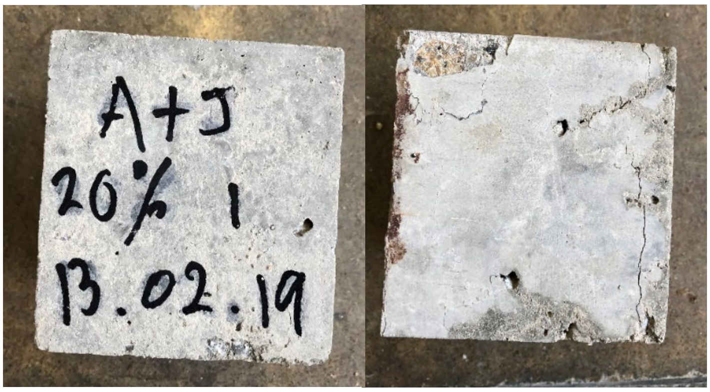

Figure 13: 100 mm^3 20 % sample 1 – after compressive strength testing

The failure mode exhibited by the reference concrete cube was that of an ideal cone failure, in accordance with the recommendation of the British Standard Institute (2009a). Cracking along the four exposed faces was equally spread, as opposed to focused along the edges and around the pores for the samples containing PET aggregate. Interface failure was exhibited rather than the creation of transverse cracks along the edge of the sample, as shown by the concrete containing PET plastic. However, as the compressive load has forced the sample to deform laterally, illustrated in Figure 14, the inclusion of PET flakes for samples P10 and P20 could have retarded this process; thus providing reason for their increase in compressive strength when compared to the reference mix.

Figure 14: 100 mm^3 reference mix sample following compression testing

With the PET aggregate being used directly from bags obtained from the manufacturing plant, graded only to a maximum size of 10mm, sufficiently small particles would have been included in the concrete mixes. A significant failure surface would not have been created between the plastic and the cement paste. Nevertheless, the fracture surface shown in Figure 14 indicates that under compressive testing, rather than fracture under tension, the plastic was able to twist and pull out, as also seen by Al-Manaseer and Dalal (1995). The vigorous recycling process used to manufacture the flakes could also have roughened the surface of the PET, thus accommodating mechanical interlock between the flakes and the cement paste.

With the inclusion of a greater volume of PET flakes the probability of having sufficiently sized flakes, ranging from those graded similar to the sand being replaced, to those large enough to bridge the cracks brought about by compressive load, increases; thus providing a reason for the higher compressive strength values shown by the P20 samples. This behaviour can also be attributed to the enhanced strength seen by the 150mm^3 samples, compared to the 100 mm^3 samples; this conflicts with the results obtained by Rahmani et al. (2013).

Split tensile strength

Interestingly following visual inspection of the cylinder samples after tensile testing, it was observed that the failure modes varied significantly between sample types. As illustrated in Figure 15, reference samples suffered complete tensile failure and

Figure 15: Reference mix sample 1 after splitting tensile failure

subsequently separated into two distinct pieces. Cracking was experienced roughly along the line of load, with a vertical failure plane evident. This behaviour was expected with similar illustrations provided by Saikia and Brito (2013).

The expected decrease in splitting tensile strength of the concrete mixes containing PET flakes can be attributed to the weak interfacial zone and bonding between the plastic and the cement paste. However, as seen in Figure 16, and in accordance with the analysis by Saikia and Brito (2013) and Yang et al. (2015), the column shaped flaky particles provided bridging action across the cracked surface; a possible explanation for the relatively insignificant change in the splitting tensile strength of the 150ø x300 mm^3 samples. This is most notable for increased percentages of plastic flakes. Fractures along the line of load were barely visible for cylindrical samples with 20 % replacement level [a) - Figure 16]. Furthermore, this implies additional loading is able to be withstood for samples containing PET flakes.

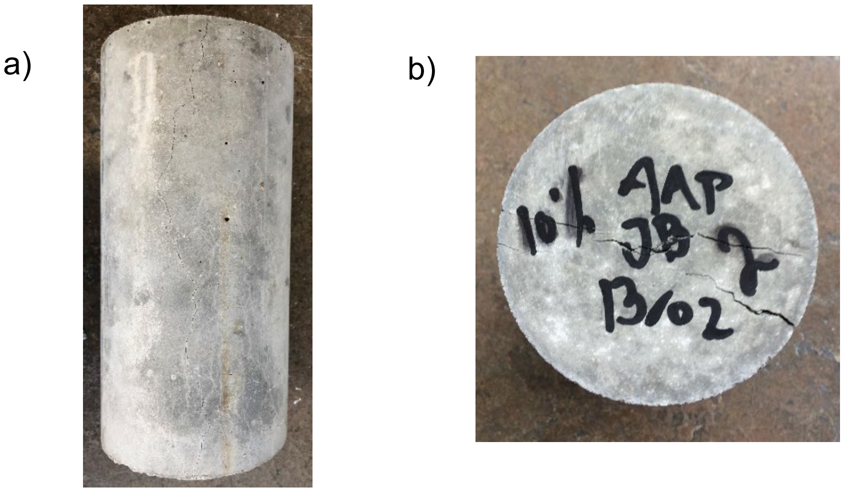

Figure 16: 150 ømm x 300 mm samples after splitting tensile failure a) 20 % replacement sample 1 b) 10 % replacement sample 2

The single values for the samples differ no more than ±0.4 MPa from the mean values, reported in Table X. Unlike the compressive strength results however, the larger 150 ømm x300 mm^3 samples exhibited lower splitting tensile strength values than the smaller samples; due to the increased number of pores in the samples. Due to the unusual trend experienced by compressive strength testing, equations to predict the splitting tensile strength were not able to validate the results. The splitting tensile strength results were greater than those seen in the reviewed literature. For example, the splitting tensile strength of the reference mixes created by Choi et al. (2005), Juki et al. (2013) and Saikia and Brito (2013) were 3.27 MPa, 3.52 MPa and 3.49 MPa, respectively.

Flexural strength

The prism moulds used to create the reference beam samples were made by hand using MDF boarding. Despite every effort to reduce human error, the maximum error of the final dimensions was ±1.2mm. For example, the dimensions of the sample 3 reference beam were 100.6 x 99.4 x 501.2 mm. Alternatively, plastic pre-made beams were used for the beams with plastic additive. The maximum error for the beams with 10 % and 20 % plastic replacement were ±3.5 mm and ±2.0 mm, respectively. In order to aid in the removal of the concrete beams from their moulds, a non-stick membrane was first laid along the base of the mould. This however, had a detrimental effect on the compaction of the concrete and subsequently created grooves in the beams, as illustrated in Figure 17.

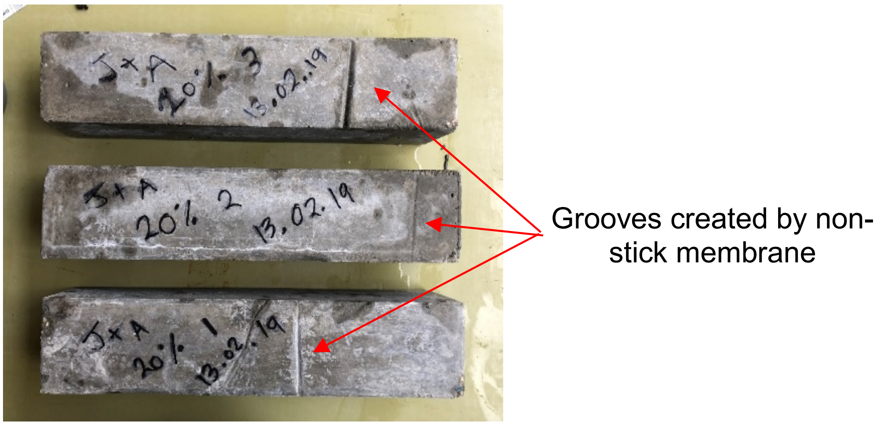

Figure 17: Concrete beams

In agreement with the conclusion by Marzouk et al. (2006), the large (maximum 10mm) sized particles used in this study are reason for the initial increase seen in flexural strength. The flakes bridge the gaps between micro-cracks brought about by flexural stress. Previous studies that saw a decrease in flexural strength for 10 % replacement of fine aggregate with PET (Batayneh et al., 2006; Marzouk et al., 2006; Ismail and Al-Hashmi, 2007; Saikia and Brito) used particles with a maximum size of 5mm (Marzouk et al., 2006).

However, it is evident from Table 2 that for up to 20 % replacement level there is no significant effect on the flexural strength of the concrete. Reference mix beam sample 3, 10 % replacement beam sample 2 and 20 % replacement beam sample 2 all exhibited flexural strength of 6.6 MPa. The flexural strength of sample 3 with 20% replacement level of PET indicates a value (5.6 MPa) that is 13% lower than the average value; thus it has been excluded from the average. It is evident from Figure X that the large groove present on the sample 3 beam would have had an effect on reducing the flexural strength. Further testing is required to confirm these results.

The beams which experienced the greatest flexural strength for each mix design are shown in Figure 18. It can be clearly seen that cracking was experienced directly below the point of load. This was expected and indicates that there were no significant deformities within the beams, leading to failure occurring at different positions along the beams.

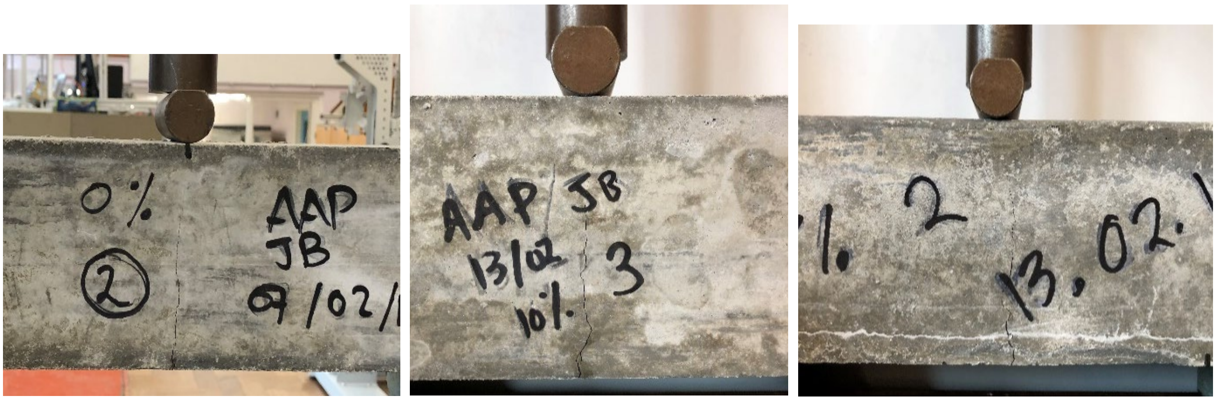

Figure 18: Concrete beam samples after flexural testing

After completing flexural tests on the beams, the samples were split in half to view the mix of materials within the concrete matrix. The sample 2 reference beam (left), the sample 3 beam with 10% replacement of PET (centre) and the sample 2 beam with 20% replacement of PET (right) are illustrated in Figure 19. A quality mix of materials within the three samples is evident; a reason for the high flexural strength values in comparison to previous studies (Juki et al., 2013; Rahmani et al., 2013; Saikia and Brito; 2013; Jibrael and Peter, 2016; Alqahtani et al., 2017). Whereas debonding is shown above in Figure 11, Figure 19 indicates a relatively strong bond between the large PET flakes and the cement paste. The angular shape of the flaked particles provides enhanced interlock, implying that the shape and size of the PET aggregate directly affects the flexural behaviour of concrete.

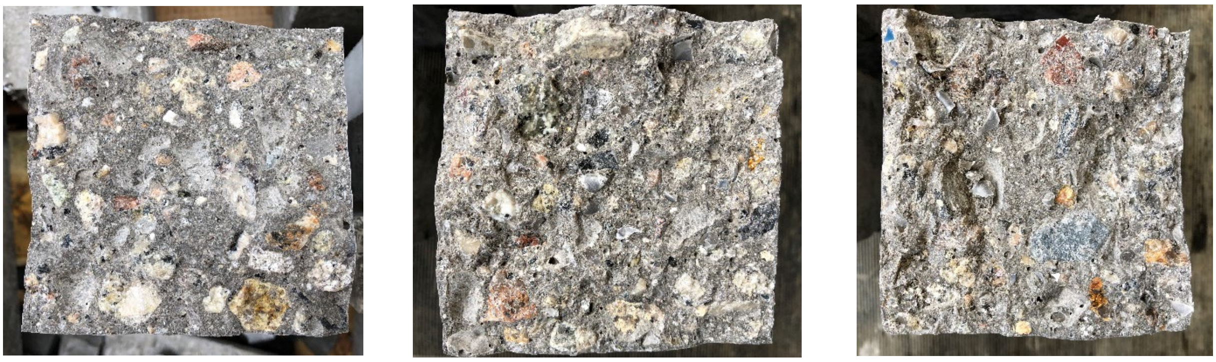

Figure 19: Concrete beam samples split open after flexural strength testing

Modulus of elasticity

The modulus of elasticity values indicated in Table 2 have been calculated from the beam samples, thus providing the flexural (bending) modulus of the concrete. As described in section 2.5.4, no apparent previous studies conducted flexural strength tests on concrete specimens containing PET. The samples containing 10 % and 20 % replacement of PET showed a correlation between the flexural strength and the modulus of elasticity values. Greater flexural strength values corresponded to greater bending modulus values, as expected. As described above, the flexibility and crack arrest properties of the PET can be attributed to the greater average modulus of elasticity results. This is indicated by the concrete containing 20 % PET replacement in comparison to the reference mix. However, the decrease in modulus of elasticity for the concrete containing 10 % PET replacement are in line with previous studies (Albano et al., 2009; Hannawi et al., 2010; Jacob-Vaillancourt and Sorelli, 2018).

By analysing the flexural stress-strain graphs in Figures 5, 6 and 7, it can be seen that a smaller range of peak strain values is obtained by the reference beam samples compared to those obtained by the samples containing PET flakes. Interestingly, the peak strain values of the samples containing 10 % replacement (Specimen 4-6) are greater than those obtained by the other 6 beams. This implies that the PET flakes would have slipped within the concrete matrix, due to the weak cohesion between the plastic and the cement paste. However, as the load was taken off the beams after the maximum stress was achieved, the low increase in strain indicates that the PET was able to bridge the cracks shown in Figure 18.

In general, for an equivalent load, PET will deform more than sand as it is less resistant to the stress. Therefore, the lower modulus of elasticity of the PET, compared to the natural aggregate (sand), is also reason for the decrease in values obtained by the beams with 10 % replacement level. The flexibility of the PET allows it to elongate when a load is applied. This subsequently allows the concrete to take additional flexural load after its maximum has been reached. Testing on additional beam samples is required to reach a definitive trend. It is clear from the results that the modulus of elasticity is directly affected by the inclusion of PET and dependant on the added percentage However, as described earlier, the samples containing PET flakes had grooves on the faces of the beams (Figure 17) which would have created areas of high stress, subsequently affecting the results.

SEM

The surface of the plastic aggregate appears to behave like a porous material, thus supporting the conclusion by Liguori et al. (2014). As a result of the exothermic reactions arising from the cement hydration process and the alkaline environment, better adherence between the plastic aggregate and the cement paste is acquired. This is evident in Figure 20, where a PET flake can be seen to protrude into the

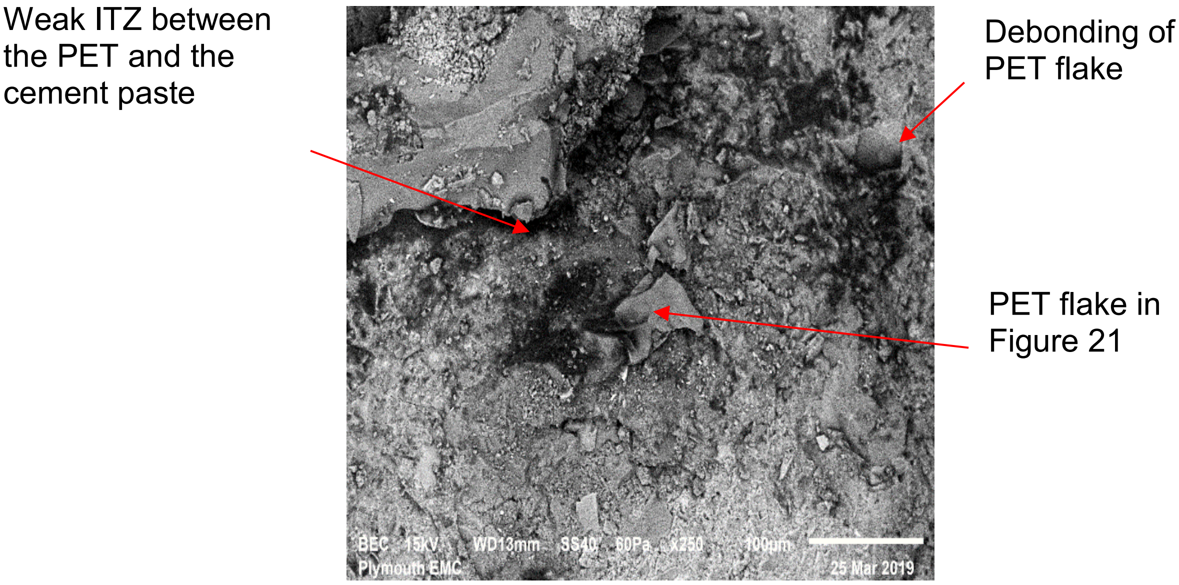

Figure 20: Concrete matrix containing PET flakes – x250 magnification

concrete without clearly repelling the matrix. This also aligns with the conclusion by Thorneycroft et al. (2018) that sufficiently small PET particles do not create a significant failure surface.

On the other hand, Figure 21 shows the weak Interfacial transition zone (ITZ) between a larger PET flake and the cement paste. When comparing this to images taken by Choi et al. (2005) of the ITZ between the natural aggregate and the cement paste, it can be clearly seen that the ITZ shown below is significantly wider (indicated by dark, sharp boundaries). To further enforce this point, debonding of a PET flake from the concrete matrix is also evident. Therefore, the reduction in mechanical strength seen above can be attributed to these two points, resulting from the hydrophobic nature of PET.

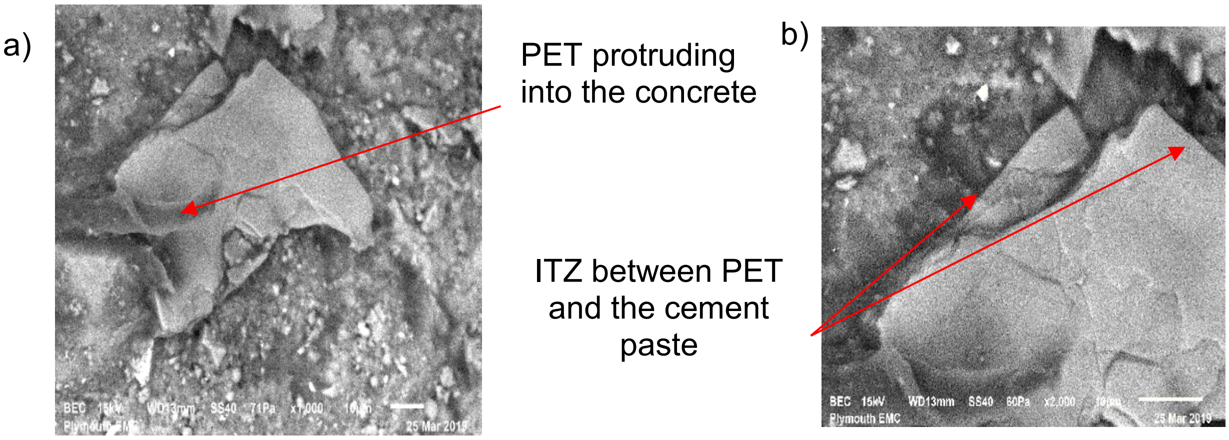

Figure 21: PET flake in concrete mix a) x1000 magnification b) x2000 magnification

Conclusion

It is clear that the use of PET plastic has the potential to evolve the construction industry. The increase in compressive strength of concrete containing 20% volumetric replacement of sand with PET indicates its use for structural and non-structural applications. The behaviour of the concrete containing PET was similar to that of the conventional reference concrete. Although in some cases providing superior failure modes. The crack arrest properties of the PET prevented complete failure of the samples, thus providing the potential to take additional load in a safe manor.

SEM imaging proved that, rather than split apart, the PET flakes simply pulled out of the concrete. This could in turn be detrimental to the environment at the end-of-life decommission or recycling of concrete elements in application. However, the ductile failure modes experienced would allow the concrete to withstand additional load without complete disintegration. Cracking was still present on the face of the concrete samples containing PET flakes, after mechanical testing. For future applications, particularly in Earthquake situations, this could prevent the total collapse of buildings and allow time for repairs to be made once cracking occurs.

Other than for the splitting tensile strength and density results, this study determined differing trends to those found in previous literature. The increases in compressive strength and modulus of elasticity, for 20% replacement level, and the flexural strength, for 10% replacement. These ultimately contradict both the results of previous studies and the predictions made for this experiment. Overall however, it can be concluded that there is significant potential for the use of up to 20 % replacement of PET in the mix design specified above for structural and non-structural applications. Ultimately, the aim and objectives of this paper were successfully investigated.

Future work

Although positive, further investigation is required to validate the results of this study. Cost – benefit analysis of using PET in structural applications must be drawn if its widespread use is to be considered. The following points highlight possible future work on this subject:

1. Investigating the long term durability effects of the concrete containing PET flakes
2. Investigating the bond between plastic concrete and steel reinforcement
3. Understanding the properties of PET and how the source affects the behaviour of the concrete
4. Investigating the combination of plastic aggregate and fibres have on the properties of concrete
5. Addressing and comparing the total construction monetary cost of producing concrete with plastic as opposed to normal conventional concrete.

Until additional research is conducted, the mix design used in this experiment should be followed if concrete is to be manufactured for structural or non-structural elements.

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References

Albano, C., Camacho, N., Hernandez, M., Matheus, A. and Gutierrez, A. (2009). Influence of content and particle size of waste pet bottles on concrete behaviour at different w/c ratios. *Waste Management*, 29(10), pp.2707-2716. Available at: https://www.sciencedirect.com/science/article/pii/S0956053X09001767

Al-Manaseer, A.A. and Dalal, T.R. (1997). Concrete containing plastic aggregates. *Concrete International*, *19*(8), pp.47-52. Available at: https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/60.

Alqahtani, F.K., Ghataora, G., Khan, M.I. and Dirar, S. (2017). Novel lightweight concrete containing manufactured plastic aggregate. *Construction and Building Materials*, 148, pp.386-397. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0950061817308863

Babu, D.S., Babu, K.G. and Wee, T.H. (2005). Properties of lightweight expanded polystyrene aggregate concretes containing fly ash. *Cement and Concrete Research*, *35*(6), pp.1218-1223. Available at: https://www.sciencedirect.com/science/article/pii/S0008884605000177.

Batayneh, M., Marie, I. and Asi, I. (2007). Use of selected waste materials in concrete mixes. *Waste management*, *27*(12), pp.1870-1876. Available at: https://www.sciencedirect.com/science/article/pii/S0956053X06002601.

Bhogayata, A.C. and Arora, N.K. (2018). Impact strength, permeability and chemical resistance of concrete reinforced with metalized plastic waste fibers. *Construction and Building Materials*, *161*, pp.254-266. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0950061817323541.

British Standards Institute (BSI), (2009a). Testing hardened concrete. *Making and curing specimens for strength tests. BS EN*, pp.12390-3. London, UK. Available at: https://shop.bsigroup.com/ProductDetail/?pid=000000000030164903

British Standards Institute (BSI), (2009b). Testing hardened concrete. *Compressive Strength of Test Specimens. BS EN*, pp.12390-3. London, UK. Available at: https://shop.bsigroup.com/ProductDetail/?pid=000000000030360096.

British Standards Institute (BSI), (2009c). Testing hardened concrete. *Flexural Strength of Test Specimens. BS EN*, pp.12390-5. London, UK. Available at: https://shop.bsigroup.com/ProductDetail/?pid=000000000030164909.

British Standards Institute (BSI), (2009d). Testing hardened concrete. *Tensile Splitting Strength of Test Specimens. BS EN*, pp.12390-6. London, UK. Available at: https://shop.bsigroup.com/ProductDetail/?pid=000000000030200045.

Building Research Institute (BREINS). (2019). *Compression Test on Concrete*. [online] Available at: http://www.buildingresearch.com.np/services/mt/mt1.php.

Choi, Y.W., Moon, D.J., Chung, J.S. and Cho, S.K., (2005). Effects of waste PET bottles aggregate on the properties of concrete. *Cement and concrete research*, *35*(4), pp.776-781. Available at: https://www.sciencedirect.com/science/article/pii/S0008884604002169.

Choi, Y.W., Moon, D.J., Kim, Y.J. and Lachemi, M., 2009. Characteristics of mortar and concrete containing fine aggregate manufactured from recycled waste polyethylene terephthalate bottles. *Construction and Building Materials*, *23*(8), pp.2829-2835. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0950061809000774.

Clean Tech Ltd. (2018). *PET Manufacturing Plant - Clean Tech UK - rPET manufacture*. [online] Clean Tech | Plastic Bottle Recycling, P.E.T Products. Available at: https://www.clean-tech.eu/manufacturing/rpet-manufacturing-plant.

Ferreira, L., de Brito, J. and Saikia, N. (2012). Influence of curing conditions on the mechanical performance of concrete containing recycled plastic aggregate. *Construction and Building Materials*, *36*, pp.196-204. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0950061812003479.

Frigione, M. (2010). Recycling of PET bottles as fine aggregate in concrete. *Waste management*, *30*(6), pp.1101-1106. Available at: https://www.sciencedirect.com/science/article/pii/S0956053X10000735.

Geyer, R., Jambeck, J.R. and Law, K.L. (2017). Production, use, and fate of all plastics ever made. *Science advances*, *3*(7), p.e1700782. Available at: https://advances.sciencemag.org/content/3/7/e1700782.short.

Gu, L. and Ozbakkaloglu, T. (2016). Use of recycled plastics in concrete: A critical review. *Waste Management*, *51*, pp.19-42. Available at: https://www.sciencedirect.com/science/article/pii/S0956053X16300915.

Han, C.G., Hwang, Y.S., Yang, S.H. and Gowripalan, N. (2005). Performance of spalling resistance of high performance concrete with polypropylene fiber contents and lateral confinement. *Cement and concrete research*, *35*(9), pp.1747-1753.

Hannawi, K., Kamali-Bernard, S. and Prince, W., (2010). Physical and mechanical properties of mortars containing PET and PC waste aggregates. *Waste management*, *30*(11), pp.2312-2320.

HM Treasury. (2018). *Tackling the plastic problem summary of responses to the call for evidence*. London, pp.6-8. Available at: https://www.gov.uk/government/consultations/tackling-the-plastic-problem.

Islam, M.J., Meherier, M.S. and Islam, A.R. (2016). Effects of waste PET as coarse aggregate on the fresh and harden properties of concrete. *Construction and Building materials*, *125*, pp.946-951. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0950061816313915.

Ismail, Z.Z. and Al-Hashmi, E.A. (2008). Use of waste plastic in concrete mixture as aggregate replacement. *Waste management*, *28*(11), pp.2041-2047. Available at: https://www.sciencedirect.com/science/article/pii/S0956053X07002784.

Jacob-Vaillancourt, C. and Sorelli, L. (2018). Characterization of concrete composites with recycled plastic aggregates from postconsumer material streams. *Construction and Building Materials*, *182*, pp.561-572. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0950061818314752

Jibrael, M.A. and Peter, F. (2016). Strength and Behavior of Concrete Contains Waste Plastic. *Journal of Ecosystem & Ecography*, *6*(2), pp.2-5. Available at: https://www.omicsonline.org/open-access/strength-and-behavior-of-concrete-contains-waste-plastic-2157-7625-1000186.php?aid=74481

Juki, M.I., Awang, M., Annas, M.M.K., Boon, K.H., Othman, N., Roslan, M.A. and Khalid, F.S. (2013). Relationship between compressive, splitting tensile and flexural strength of concrete containing granulated waste Polyethylene Terephthalate (PET) bottles as fine aggregate. In *Advanced materials research*(Vol. 795, pp. 356-359). Trans Tech Publications. Available at: https://www.scientific.net/AMR.795.356

Marzouk, O.Y., Dheilly, R.M. and Queneudec, M., (2007). Valorization of post-consumer waste plastic in cementitious concrete composites. *Waste management*, *27*(2), pp.310-318. Available at: https://www.sciencedirect.com/science/article/pii/S0956053X06001048

Ochi, T., Okubo, S. and Fukui, K. (2007). Development of recycled PET fiber and its application as concrete-reinforcing fiber. *Cement and Concrete Composites*, *29*(6), pp.448-455.

Otani, L.B., Pereira, A.H.A., Melo, J.D.D. and Amico, S.C. (2014). Elastic Moduli characterization of composites using the Impulse Excitation. *ATCP Physical Engineering*. Available at: https://sonelastic.com/images/downloads/ITC-06-IET-MOE-Composites-v1.3.pdf.

Rahmani, E., Dehestani, M., Beygi, M.H.A., Allahyari, H. and Nikbin, I.M., (2013). On the mechanical properties of concrete containing waste PET particles. *Construction and Building Materials*, *47*, pp.1302-1308. Available at: https://www.sciencedirect.com/science/article/abs/pii/S095006181300559X.

Saikia, N. and de Brito, J., (2013). Waste polyethylene terephthalate as an aggregate in concrete. *Materials Research*, *16*(2), pp.341-350. Available at: http://www.scielo.br/scielo.php?script=sci_arttext&pid=S1516-14392013000200011.

Saikia, N. and de Brito, J. (2014). Mechanical properties and abrasion behaviour of concrete containing shredded PET bottle waste as a partial substitution of natural aggregate. *Construction and building materials*, *52*, pp.236-244. Available at: https://www.sciencedirect.com/science/article/abs/pii/S0950061813010817.

Sand Wars, an investigation documentary. (2013). [film] Directed by D. Delestrac. France: Rappi productions.

Saxena, R., Siddique, S., Gupta, T., Sharma, R.K. and Chaudhary, S. (2018). Impact resistance and energy absorption capacity of concrete containing plastic waste. *Construction and Building Materials*, *176*, pp.415-421.Available at: https://www.sciencedirect.com/science/article/abs/pii/S0950061818310948.

Silva, R.V., de Brito, J. and Saikia, N. (2013). Influence of curing conditions on the durability-related performance of concrete made with selected plastic waste aggregates. *Cement and Concrete Composites*, *35*(1), pp.23-31. Available at: https://www.sciencedirect.com/science/article/pii/S0958946512001813.

Song, P.S., Hwang, S. and Sheu, B.C. (2005). Strength properties of nylon-and polypropylene-fiber-reinforced concretes. *Cement and Concrete Research*, *35*(8), pp.1546-1550.

Suganthy, P. and Chandrasekar, D. (2013). Utilization of pulverized plastic in cement concrete as fine aggregate. Available at: http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.676.5751.

Tandon, S. and Faber, K.T. (1993). Fracture of brittle and quasi-brittle engineering materials.

Teychenné, D.C., Franklin, R.E., Erntroy, H.C. and Marsh, B.K., (1988). *Design of normal concrete mixes.* 2nd Ed. HM Stationery Office. Available at: https://www.brebookshop.com/samples/327970.pdf.

Thorneycroft, J., Orr, J., Savoikar, P. and Ball, R.J. (2018). Performance of structural concrete with recycled plastic waste as a partial replacement for sand. *Construction and Building Materials*, *161*, pp.63-69. Available at: https://www.sciencedirect.com/science/article/pii/S0950061817323474.

United Nations Environment Programme (UNEP) (2018). *Sweden and UN Environment announce $6 million project to beat plastic pollution in Southeast Asia*. [online] Available at: https://www.unenvironment.org/news-and-stories/press-release/sweden-and-un-environment-announce-6-million-project-beat-plastic.

Yang, S., Yue, X., Liu, X. and Tong, Y., (2015). Properties of self-compacting lightweight concrete containing recycled plastic particles. *Construction and Building Materials*, *84*, pp.444-453.

Zeenews (2010) *Sand mining ban in Maharashtra threatens mega projects*. [online]. Available at: http://zeenews.india.com/news/maharashtra/sand-mining-ban-inmaharashtra-threatens-mega-projects_659907.html.